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No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils

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ABSTRACT

Many soils in the semiarid Mediterranean Ebro Valley of Spain are prone to physical and chemical degradation due to their silty texture, low organic matter content, and presence of carbonates, gypsum or other soluble salts. Rainfed agriculture on these soils is also hindered by the scarcity of water. No-tillage can increase plant-available water and soil organic matter, thus helping overcome most factors limiting crop production in this area. Our objective was to determine how conventional- and no-tillage practices affected soil physical quality indicators and water availability in an on-farm study in the Ebro Valley. Soil samples were collected from 0 to 5-, 5 to 15-, and 15 to 30-cm depth increments within adjacent farmer-managed conventional- and no-tillage fields in 2007 and 2008. Both fields were managed for continuous barley (*Hordeum vulgare* L.) production. The soil at both sites is a silt loam (*Haplic Calcisol*). Aggregate-size distribution and stability, soil water retention characteristics, organic carbon, and total carbonates were determined in 2007. Pore-size distribution was estimated from the water retention curve. Penetration resistance, soil bulk density and field water content during the entire crop growing season were measured for both fields in 2008. Aggregate dry mean weight diameter and stability in water were 1.2 and 2.2 times greater, respectively, under no-tillage than conventional tillage due to reduced mechanical disturbance and increased soil organic carbon content. Bulk density was 1.12 times greater ($P < 0.1$) under no-tillage only in the 0–5-cm depth. Two times greater penetration resistance to a depth of 15 cm in this treatment was related to bulk density and aggregates stability. Field water content was greater with no-tillage than conventional tillage during the driest months in 2008. The volume of equivalent diameter pores (0.2–9 μm) was 1.5 times higher under no-tillage. This increased plant-available water content and doubled barley production under no-tillage in 2008, which was a very dry year. We conclude that despite the greater penetration resistance under no-tillage, increased water availability as a result of improved structure characteristics was more important for crop yield. This suggests that producers should seriously consider adopting no-tillage practices for soil conservation in semiarid degraded areas like the one studied.

1. Introduction

Soil physical properties strongly influence soil function and determine potential land uses. This is of special importance in the Ebro Valley of Spain, where they affect both plant-available water content and land degradation processes. Water frequently limits rainfed crop production in this area because of low precipitation (<450 mm) and an uneven interannual distribution. To mitigate that stress it is crucial to enhance plant-available water content which is directly affected by soil structure. This enhancement can be difficult, however, because soils of the Ebro Valley are usually characterized by silty texture, low organic matter content, localized accumulations of both geological and secondary gypsum and other soluble salts; factors affecting soil structure and resulting in a high potential for physical and chemical degradation.

Chisel-ploughing is one management practice that has been introduced for dryland production in the Ebro Valley during the last 20 years to decrease damage to soil structure (Angás et al., 2006). No-tillage is not used as much (10–30% of the land) even though it may be a better option to prevent soil degradation and increase plant-available water. The most widely used practice (i.e. conventional tillage in the area) is reduced vertical tillage with a chisel-plough.

To evaluate effects of management on soil physical quality, aggregate-size distribution, water stability of those aggregates,

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Table 1
General soil characteristics and particle size distribution under no-tillage (NT) and conventional tillage (CT) in 2007.

Tillage treatment	NT			CT		
Soil depth (cm)	0–5	5–15	15–30	0–5	5–15	15–30
Particle size distribution USDA (g/kg)						
Sand (50–2000 μm)	160.5	147.3	141.6	171.4	147.9	139.2
Silt (2–50 μm)	579.4	582.6	574.0	572.4	609.4	607.2
Clay (<2 μm)	260.0	270.3	284.3	256.2	242.6	243.6
Organic carbon (g/kg)	12.55	9.68	9.32	10.17	9.63	8.45
$CaCO_3$ (g/kg)	356	362	353	353	349	353
pH (water, 1:2.5)	8.39	8.51	8.50	8.35	8.47	8.50
Electrical conductivity (1:2.5) (dS/m)	0.15	0.13	0.12	0.24	0.13	0.16
Cation exchange capacity ($cmol_c$+/kg)	12.41	15.22	13.33	10.98	15.10	11.50

compaction, water retention and porosity have been widely used as soil quality indicators and are often referred to as dynamic physical quality indicators. Collectively assessing multiple indicators such as these, along with those reflecting biological and chemical properties and processes can be useful for quantifying changes in soil quality due to various management practices (Karlen, 2004).

One reason for suppression of tillage is that it temporarily alters soil structure, breaking apart the largest soil aggregates and disrupting their formation and stabilization cycles (Six et al., 1999). Most of the studies on this topic have been conducted on carbonate-free, neutral to acidic soils, as in Rasmussen (1999) for Scandinavian soils, Castro-Filho et al. (2002) for a Brazilian latosol, Zhang et al. (2007) for an Australian oxisol, and many others. They generally observed a higher mean weight diameter for dry aggregates and a greater percentage of water stable aggregates as tillage intensity decreased. Studies quantifying tillage effects on aggregation in calcium-rich soils, such as those in the Ebro Valley, where calcium plays an important role in the aggregate cycle (Muneer and Oades, 1989), are more scarce in the literature. Recently, Álvaro-Fuentes et al. (2007) observed that organic matter enrichment under no-tillage also enhanced aggregate stability in a loam calcic soil under similar semiarid conditions.

Tillage is often justified because without it compaction can lead to higher bulk density and increased penetration resistance, especially in the top few centimetres of soil. Many authors have found that semiarid no-tillage sites have greater bulk density and penetration resistance than reduced-tillage sites (e.g. Mahboubi et al., 1993; Lampurlanés and Cantero-Martínez, 2003). Such compaction is often characterized by a reduction in size distribution and stability of aggregates; two soil structure factors that provide resistance against external forces (e.g. wheel traffic).

Tillage and the resultant soil structure also influence soil water retention and its availability to plants. This is especially critical for crop production and temporal yield stabilization under semiarid conditions. No-tillage has been shown to increase soil water content through greater infiltration and reduced evaporation (Blevins and Frye, 1993; Cannell and Hawes, 1994; Lampurlanés et al., 2001), and by increasing the proportion of smaller pores (Arshad et al., 1999; Bescansa et al., 2006).

We hypothesized that no-tillage can provide an opportunity to improve soil structure and increase plant-available water content in soils that have lost in some degree of ability to sustain crop production, as a result of decreased physical and/or biochemical quality, under the semiarid conditions in the Mediterranean Ebro Valley of Spain. Our objectives were to quantify soil physical quality indicators and water retention characteristics for two, adjacent farmer-managed fields, one conventional- and one no-tillage, where rainfed barley was being grown. Through this analysis, we wanted to quantify the sustainability of no-tillage for this semiarid area where soils have a little structure development and high potential for degradation due to their physicochemical properties, and where water is the most limiting factor for crop production.

2. Materials and methods

2.1. Site description and experimental design

This study was conducted at two adjacent on-farm sites in the Ebro Valley following 7 years of either conventional- or no-tillage practices near the municipality of Santacara (42°23′44″N; 1°32′32″W; altitude 342 m a.s.l.) in the southern portion of Navarre. Conventional tillage (CT, consisting of chisel-ploughing to a depth of 15 cm) has been practiced for decades in the area. No-tillage (NT, using direct-seeding) was implemented in one of the fields in 2000, 7 years before this study was conducted. Both fields were managed for continuous barley (*Hordeum vulgare* L.) production, using the same seeding rate (160 kg/ha) and fertilizer treatments. The soil at both sites is a silt loam *Haplic Calcisol* (Word Reference Base, FAO, 2003) with high calcium carbonate content. Organic carbon content in both fields is low and decreases with depth. The slope is negligible in both fields. Additional details for both sites are given in Table 1.

Climate in the area is semiarid Mediterranean with an autumn/winter rainfall pattern and dry, hot summers. The average (30 years) annual precipitation is 448 mm with an evapotranspiration of 775 mm. Averages for the growing season (October to July) are 389 and 553 mm, respectively. During the two seasons that this research was conducted, (October 2006 through July 2008) mean rainfall was 494 and 338 mm, respectively (Table 2).

Fields for each tillage treatment were selected randomly within the same soil unit and treated as experimental units based on the model of Wander and Bollero (1999). Within each field a 12 m × 12 m grid was established. The main treatment was the tillage system (CT versus NT). Samples were collected at the four grid corners within each field, for three depth increments (0–5, 5–15, and 15–30 cm) in 2007 and 2008.

2.2. Soil sampling, laboratory analyses and field measurements

Soil organic carbon content (SOC) and total carbonate content were analysed in composite samples previously air-dried and sieved to pass a 2-mm sieve, in 2007. Due to the elevated carbonate

Table 2
Long-term average and seasonal rainfall and evapotranspiration at the study site in the Ebro Valley of Spain.

	Annual average (30 years)	Growing season (average)	Growing season 2006–2007	Growing season 2007–2008
Rainfall (mm)	448	389	494	338
ETP[a] (mm)	775	553		

[a] ETP, potential evapotranspiration (Thornthwaite).

content (Table 1), wet oxidation (Walkley-Black) was used to analyze total oxidizable C (Tiessen and Moir, 1993), from which we calculated total organic C. Carbonates were measured by acid digestion using a Bernard calcimeter (Bonneau and Souchier, 1979).

Soil aggregation was characterized by the dry aggregate-size distribution and water stability. Undisturbed samples were collected in 2007 from the three depth increments. Dry aggregate-size distribution was measured by placing 80 g of air-dried soil, that had previously been gently forced to pass through 8 mm-opening sieve, on top of a column of sieves with 4, 2, 1, 0.50, and 0.25 mm openings and shaken with rotary movement at 60 strokes/min for 60 s using a Retsch Vs 1000 device (Retsch GmbH & Co., Hann, Germany). For the water aggregate stability, a constant shower-like flux (2 L/min) of water was applied from the top of the same set of sieves while shaking at 60 strokes/min for 60 s. The mean weight diameter (MWD), calculated by summing the product of aggregate fractions and mean diameter for each class, was used to express dry aggregate-size distribution (Kemper and Chepil, 1965). The water stable aggregate percentage (WSA) was calculated as the sum of the ratios of stable aggregate weight in each fraction to total sample weight corrected for sand (Kemper, 1965).

Soil water retention (SWR) characteristics were measured in 2007 in 5 and 15 pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA) as described by Dirksen (1999). Water retention at a matric potential of −33 kPa, was measured using undisturbed soil samples. Sieved samples at 2 mm were used to measure SWR at −50 and −1500 kPa. Volumetric values for SWR were calculated from the gravimetric measures using bulk density. Total plant-available water content (AWC) was calculated from the difference in soil moisture content at field capacity (−33 kPa) and permanent wilting point (−1500 kPa).

As described in Bescansa et al. (2006), the model proposed by Rose (1966) was used to estimate the equivalent pore diameter corresponding to each of the water potentials. According to this model, equivalent pore diameter was 9 μm for −33 kPa, 6 μm for −50 kPa, and 0.2 μm for −1500 kPa.

Penetration resistance (PR) from 0- to 30-cm depth, at intervals of 15 mm, was measured in each field with a Rimik CP20 cone penetrometer in March 2008. This instrument measures the mean vertical strength required to introduce a steel cone of 6.3 cm^2 (diameter = 1.28 cm, angle = 30°) into the soil. Each field was divided into four areas and measurements were taken at five points in each along a zigzag transect. At the same time, disturbed and undisturbed soil samples were collected to determine field water content (FWC) and bulk density, respectively.

The field water content was determined gravimetrically in disturbed samples, at the end of February, May, June, and September 2008. Field plant-available water content (FAWC) was calculated from the difference between FWC and the soil moisture content at permanent wilting point.

Meteorological data to calculate monthly rainfall was obtained from the local Meteorological Service of Navarre (http://meteo.navarra.es) and the National Meteorological Agency of Spain (AEMet, www.aemet.es).

Barley yields were obtained from the extension service after harvesting the entire fields. Grain yields for the two sites in 2007 and 2008 were calculated as the total dry weights per unit area and are expressed as kg/ha.

2.3. Statistical analysis

Data were analysed using ANOVA (univariate linear model). Treatment means were compared using significant differences ($P < 0.05$), and post hoc analysis was performed by Duncan test ($P < 0.05$). Unless otherwise stated, significant results are based on a probability level of $P = 0.05$. All statistical analyses were performed using SPSS 15.0 software (SPSS Inc., 2008, Chicago IL).

Table 3
Soil organic carbon (SOC) and calcium carbonate ($CaCO_3$) under no-tillage (NT) and conventional tillage (CT). Mean ± standard error.

	Soil depth (cm)		
	0–5	5–15	15–30
SOC (g/kg)			
NT	12.55 ± 0.22* (a)	9.68 ± 0.12 (b)	9.32 ± 0.15* (b)
CT	10.17 ± 0.14 (a)	9.63 ± 0.14 (b)	8.45 ± 0.08 (c)
SOC (Mg/ha)			
NT	11.15 ± 0.19*	15.95 ± 0.19	23.51 ± 0.39*
CT	8.06 ± 0.11	15.84 ± 0.23	20.82 ± 0.21
$CaCO_3$ (g/kg)			
NT	356.33 ± 2.11	362.48 ± 4.67	353.21 ± 4.49
CT	353.32 ± 6.35	348.85 ± 6.27	353.08 ± 4.42

Parameters expressed in g/kg are based on dry soil mass.
Values in the same column followed by asterisk (*) are significantly different at $P < 0.05$ according to ANOVA. Values in the same row followed by different letters belong to different Duncan's homogeneous groups ($P < 0.05$).

3. Results

3.1. Soil organic carbon and carbonates, and barley yields

Soil organic carbon (g/kg and Mg/ha) was significantly greater under NT than CT for the 0-5- and 15–30-cm depths. No differences were observed for the 5–15-cm depth (Table 3). Under NT, SOC (g/kg) was significantly greater for the 0–5 cm than 5–15- and 15–30-cm depths, but no differences were observed among 5–15- and 15–30-cm depths. With CT, SOC (g/kg) was significantly greater in the 0–5-cm depth than 5–15-cm depth, which in turn was greater than in the 15–30-cm depth (Table 3). There was no difference in carbonate content for either tillage practice or depth increment (Table 3).

Barley yields in 2007 were similar under NT and CT (3500 kg/ha). In 2008, production was 2000 kg/ha for NT and 1000 kg/ha for CT treatments.

3.2. Dry aggregate-size distribution and water stability

Dry aggregate-size distribution and water stable aggregation both showed significant differences between tillage treatments and among depths. Dry MWD for the 0–5-cm depth was significantly greater in NT than CT, but no significant differences were observed between treatments for the 5–15-cm depth. Dry MWD was again significantly greater under NT than CT practices for the 15–30-cm depth (Table 4). At 0–5- and 5–15-cm depths, WSA was significantly greater for the NT than the CT site. No

Table 4
Aggregate dry mean weight diameter (dry MWD) and water stable aggregates percentage (WSA) under no-tillage (NT) and conventional tillage (CT). Mean ± standard error.

	Soil depth (cm)		
	0–5	5–15	15–30
Dry MWD (mm)			
NT	3.16 ± 0.12*	3.19 ± 0.05	3.50 ± 0.09*
CT	2.58 ± 0.19	3.10 ± 0.11	3.11 ± 0.12
$WSA_{>0.25\,mm}$ (%)			
NT	13.60 ± 2.19*	15.05 ± 1.76*	14.33 ± 3.20
CT	5.49 ± 1.02	7.61 ± 1.29	10.62 ± 1.41

Values in the same column followed by asterisk (*) are significantly different at $P < 0.05$ according to ANOVA.

Table 5
Penetration resistance (PR), bulk density (BD), and field water content (FWC) under no-tillage (NT) and conventional tillage (CT). Mean ± standard error.

	Soil depth (cm)		
	0–5	5–15	15–30
PR (MPa)			
NT	3.37 ± 0.13*	3.51 ± 0.09*	3.82 ± 0.03
CT	1.33 ± 0.19	2.16 ± 0.17	3.72 ± 0.05
BD (g/cm^3)			
NT	1.78 ± 0.02 §	1.65 ± 0.01	1.68 ± 0.06
CT	1.58 ± 0.09	1.64 ± 0.06	1.64 ± 0.07
FWC (m^3/100 m^3)			
NT	25.21 ± 0.56 *	21.69 ± 0.77	21.96 ± 1.18
CT	20.37 ± 1.28	20.41 ± 0.58	20.75 ± 1.31

Values in the same column followed by asterisk (*) are significantly different at $P < 0.05$ according to ANOVA. Values in the same column followed by § are significantly different at $P < 0.1$.

differences were found between treatments for the 15–30-cm increment (Table 4).

3.3. Penetration resistance and bulk density

Penetration resistance in the NT and the CT fields was measured 5 months after seeding. Bulk density and field water content were determined at the same time, because those factors significantly affect PR (Busscher et al., 1997; Unger and Jones, 1998). Bulk density for the 0–5-cm depth was significantly greater under NT than CT at $P < 0.1$. For the 5–15- and 15–30-cm depths no significant differences were observed between tillage treatments. The FWC was significantly greater in the NT than the CT treatment only in the 0–5-cm depth (Table 5). The PR values for 0–5- and 5–15-cm depths were significantly greater under NT than CT (Table 5 and Fig. 1). Below 15 cm no differences were found between treatments. Penetration resistance under NT showed a uniform distribution in depth; however under CT it increased considerably between 10.5 and 13.5 cm (Fig. 1).

3.4. Rainfall and field water content during the growing season 2007–2008

Field water content and monthly rainfall were monitored from October 2007 to September 2008. This included the driest growing season (October to July) for the last 30 years, with total rainfall being about 13% below normal (Table 2).

The field water content during the growing season varied according to rainfall distribution. The values in February and May for the 0–5-cm depth, were significantly greater under NT than CT (Fig. 2). Field available water content from 0 to 30 cm in February was also significantly greater under NT than CT. In May, FAWC was similar for both treatments, coinciding with a higher rainfall rate (Fig. 3). For the June sampling, the FWC at all three depth increments and FAWC (0–30 cm) were significantly greater for the NT than CT treatment (Figs. 2 and 3). This coincided with a much lower rainfall in June than in May. After the dry summer season, FWC at 0–5 and 15–30 cm and FAWC in September were significantly greater under NT than CT (Figs. 2 and 3).

3.5. Soil water retention characteristics and pore-size distribution

Soil water retention characteristics were different between tillage practices at all three depth increments. The SWR at field capacity was significantly greater for NT than CT (Table 6). These differences were particularly noticeable in the surface depth where water retention was 23% lower with CT than NT. At the permanent

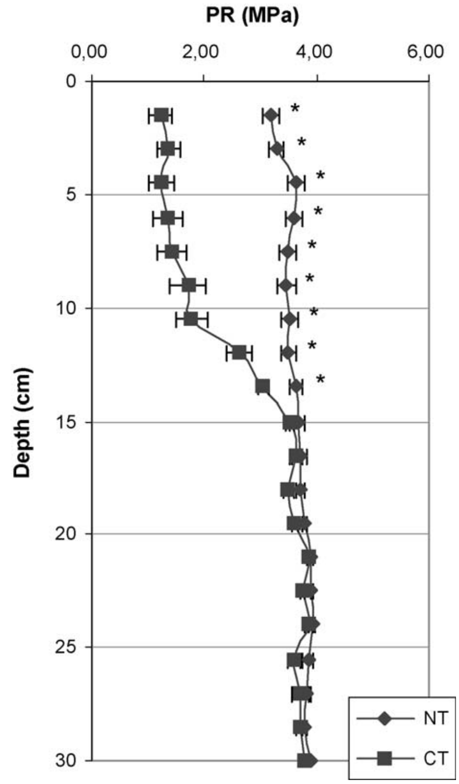

Fig. 1. Penetration resistance (PR) under no-tillage (NT) and conventional tillage (CT). Values followed by asterisk (*) within each depth are significantly different at $P < 0.05$ according to ANOVA.

wilting point, water retention was significantly greater only for the 0–5-cm depth (Table 6). Plant-available water content for the three depth increments was significantly greater under NT than CT (Table 6). Greater differences were also observed for the 0–5-cm depth, where AWC was 32.6% lower with CT than NT.

Water retention characteristics were used to estimate the pore-size distribution in the soil as in Bescansa et al. (2006). These authors assumed that pores are cylindrical capillaries as described by the Laplace–Young equation (Leij et al., 2002). Total pore volume for the 0–5-cm depth, as estimated from bulk density data, was significantly decreased under NT than CT ($P < 0.1$). Tillage significantly affected the pore-size distribution in the two fields. With NT small pores (0.2–9 μm) occupied most of the total soil pore volume, 79% in the 0–5-cm depth and about 52% in the 5–15- and 15–30-cm depths (Table 7). At the same time, with CT large pores (>9 μm) were more abundant, 57% in the 0–5-cm depth and about 59% in the 5–15- and 15–30-cm depth (Table 7). Among the small pores, those between 0.2 and 6 μm occupied the majority of the pore volume for both treatments. These pores were affected only at the 0–5- and 15–30-cm depths, with 40% and 4% more volume of those pores under NT than CT, respectively. Differences among treatments were the greatest for pores between 6 and 9 μm, with those pore sizes accounting for 56%, 68%, and 43% more volume for the three depth increments, respectively, under NT than CT (Table 7).

4. Discussion

4.1. Soil aggregation

The description and quantification of soil aggregation are important because many agronomic and environmental processes are related to soil structure. At our site where the soil has little

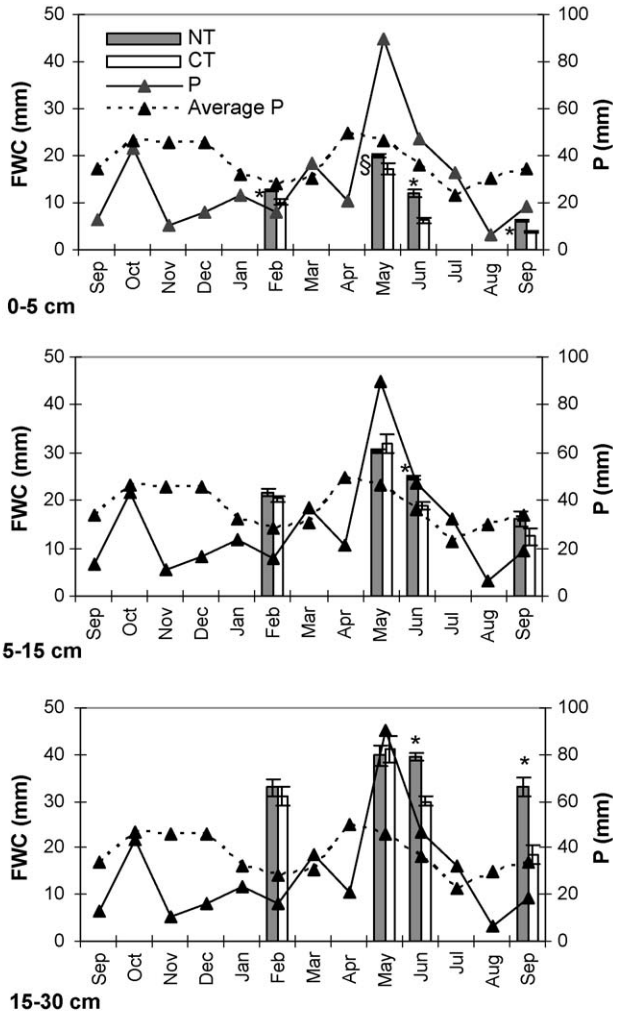

Fig. 2. Monthly field water content (FWC) and precipitation (P) for all three depth increments (0–5, 5–15, and 15–30 cm) from September 2007 to September 2008 and the average of 30 years, under no-tillage (NT) and conventional tillage (CT). The field water content was measured at the end of each month. Bars marked with asterisk (*) within the same sampling date are significantly different at $P < 0.05$ according to ANOVA. Bars marked with § are significantly different at $P < 0.1$.

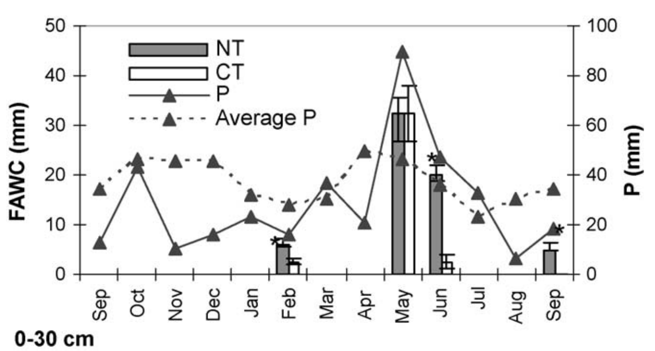

Fig. 3. Monthly field available water content (FAWC) and precipitation (P) in 0–30-cm depth from September 2007 to September 2008 and the average of 30 years, under no-tillage (NT) and conventional tillage (CT). The field available water content was determined with the FWC measured at the end of each month. Bars marked with asterisk (*) within the same sampling date are significantly different at $P < 0.05$ according to ANOVA.

structure development, suppression of tillage improved aggregate-size distribution and stability. Dry MWD was greater under NT than CT at all three depth increments (Table 4). This was in agreement with results obtained by Mrabet et al. (2001) in

Table 6
Soil water retention characteristics under no-tillage (NT) and conventional tillage (CT). Mean ± standard error.

Matric potential of water	Soil depth (cm)		
	0–5	5–15	15–30
Soil water retention ($m^3/100\,m^3$)			
Field capacity (−33 kPa)			
NT	42.56 ± 0.36*	36.47 ± 0.32*	36.59 ± 0.25*
CT	32.78 ± 0.32	33.21 ± 0.10	32.95 ± 0.19
Permanent wilting point (−1500 kPa)			
NT	19.20 ± 0.19*	18.33 ± 0.10	18.82 ± 0.16
CT	17.05 ± 0.19	18.38 ± 0.14	19.02 ± 0.11
Total available water content (mm)			
−33 to −1500 kPa			
NT	11.68 ± 0.20*	18.14 ± 0.40*	26.65 ± 0.55*
CT	7.87 ± 0.21	14.83 ± 0.21	20.89 ± 0.20

Values in the same column followed by asterisk (*) are significantly different at $P < 0.05$ according to ANOVA.

Table 7
Total pore volume and pore-size distribution under no-tillage (NT) and conventional tillage (CT). Mean ± standard error.

Pore-size distribution	Soil depth (cm)		
	0–5	5–15	15–30
Total pores (>0.2 μm)	m^3/m^3		
NT	0.30 ± 0.01§	0.35 ± 0.01	0.33 ± 0.02
CT	0.37 ± 0.04	0.35 ± 0.02	0.35 ± 0.03
Equivalent pore diameter	Relative frequency (%)		
0.2–9 μm			
NT	79.07 ± 1.39*	52.32 ± 1.18*	53.21 ± 1.11*
CT	42.34 ± 1.15	42.57 ± 0.60	39.96 ± 0.39
0.2–6 μm			
NT	56.41 ± 0.91*	39.24 ± 1.75	38.93 ± 1.02*
CT	34.02 ± 0.36	39.29 ± 0.57	37.27 ± 1.13
6–9 μm			
NT	21.37 ± 1.25*	12.05 ± 1.67 *	14.26 ± 1.86*
CT	9.33 ± 0.67	3.79 ± 0.13	8.06 ± 1.11
>9 μm			
NT	20.93 ± 1.39	47.68 ± 1.18	46.79 ± 1.11
CT	57.66 ± 1.15*	57.43 ± 0.60*	60.04 ± 0.39*

Values in the same column followed by asterisk (*) are significantly different at $P < 0.05$ according to ANOVA. Values in the same column followed by § are significantly different at $P < 0.1$.

Morocco and Álvaro-Fuentes et al. (2007) in Spain, who both evaluated cereal production systems on semiarid, carbonate-rich soils. The WSA was also significantly greater in the 0–5- and 5–15-cm depths with NT than CT (Table 4). Several authors have found an increase of WSA for different soil conditions, especially in the surface layer shortly after converting from CT (i.e. mouldboard ploughing) to NT (Arshad et al., 1998; Angers, 1998; Martínez et al., 2008), and when evaluating long term no-tillage effects (Mahboubi et al., 1993; Hernanz et al., 2002).

Two reasons can explain this behavior in the studied fields. On one hand, tillage broke the largest aggregates into smaller units through mechanical action under CT, reducing the dry MWD compared to NT. On the other hand, there was more accumulation of plant residues in NT because of the greater primary production, especially in the driest growing seasons. As a result, SOC content was greater under NT, although mainly in the surface depth (Table 3). We attribute the observed improvement of aggregate stability (WSA) to this enrichment in SOC, because no changes in calcium carbonate concentration and distribution, which are known to influence aggregation of soils such as those studied here (Muneer and Oades, 1989; Bronick and Lal, 2005), were observed (Table 3). This is in agreement with many other authors who have evaluated the role of SOC in aggregate stabilization processes under different soil conditions (e.g. Franzluebbers and Arshad, 1996; Six et al., 1999; Gale et al., 2000).

4.2. Soil bulk density and strength properties

After seven years of consecutive barley production, bulk density was significantly greater ($P < 0.10$) under NT than CT only in the 0–5-cm depth (Table 5). Gradual compaction due to reduced soil pore volume and changes in pore-size distribution during early years of NT on high-carbonate soils was also observed by Bescansa et al. (2006). Similarly, Wander and Bollero (1999) reported bulk density of 1.62 g/cm^3 following recent adoption of NT compared to 1.55 g/cm^3 under CT on loess soils in Illinois.

In addition to bulk density, PR was also measured in both fields. In general, PR in the 0–30-cm depth was high in both fields because of the high silt content, low organic matter levels, and the low moisture at the time of measurement. Penetration resistance was significantly lower in the 0–5- and 5–15-cm depths under CT than NT, coinciding with the tilled depth (about 15 cm). Tillage created a loose soil structure in the affected soil depth. As a consequence, these lower values of PR were observed only in the tilled zone (Fig. 1). Similar effects of tillage on PR have also been observed by others (e.g. Moreno et al., 1997; Taboada et al., 1998; Wander and Bollero, 1999; Schjønning and Rasmussen, 2000; Lampurlanés and Cantero-Martínez, 2003). The uniform distribution of PR with depth under NT (Fig. 1) also agrees with results reported by Tebrügge and Düring (1999) after tillage suppression. In this treatment, higher PR values (between 3.37 and 3.51 MPa) were observed in the upper soil depth (0–15 cm). Several authors have agreed that PR values greater than 2 MPa can restrict root development and negatively affect crop yield (Atwell, 1993; Hadas, 1997; Carter, 2002). However Ehlers et al. (1983) observed that despite having greater PR and bulk density values under NT, plant roots can grow within bio-pores and cracks in the soil. This seems to be the case at our site, where barley yields were equal or higher under NT than CT in both years.

When PR was measured, FWC was significantly greater for the 0–5-cm depth under NT than CT, and yet PR was greater under NT. At the 5–15-cm depth there was no difference in BD and FWC, but PR was significantly greater in the NT than CT treatment (Table 5). The difference in PR between the two treatments seems to be thus related not only to the greater BD but also to the increased water stability of aggregates under NT in the 0–5-cm depth (Tables 4 and 5), especially if we consider that the actual soil water content expressed as the percentage of water retained at field capacity was very similar under NT and CT (59% and 61%, respectively). At the 5–15-cm depth, greater PR under NT seems to be more associated to the increased water stability of aggregates in this treatment (Table 4). It is important to notice also that PR and BD values showed a greater variability under CT than NT (Table 5) in the two depth increments.

4.3. Field water content, water retention characteristics and pore-size distribution

Water retention at −33 kPa depends on soil structure (Dexter, 2004) and therefore it is affected more by tillage than water retention at −1500 kPa which is generally controlled by soil texture. Field water content in the two fields during the 2007/2008 growing season was affected by both weather and tillage practices. Throughout the season, FWC followed the monthly precipitation trend for both CT and NT (Fig. 2). Early in the season (October to April) rainfall was 40% below the long-term monthly average, so the FWC and FAWC measured in February were very low (Figs. 2 and 3). Above-average rainfall of 62% later in the growing season (May to July) increased both FWC and FAWC, but this was not enough to compensate for the dry winter effects on barley yield, which was two times greater under NT than CT in 2008 compared to similar yields in both fields in 2007. In September FWC and FAWC were again low due to a dry summer period, being 60% below the long-term average (Figs. 2 and 3).

Comparing NT and CT, the effect of tillage was most noticeable on the driest months. This was already observed in February (0–5-cm depth), and confirmed in June and September, when greater FWC and FAWC under NT than CT were observed in the entire studied depth (0–30 cm) (Figs. 2 and 3). This difference affected barley production as shown above with yields being twice as high with NT compared to CT in the driest studied year. The results were directly related to the improvement of the soil water retention characteristics under NT compared to CT. Soil water retention was significantly greater under NT for all three depth increments at field capacity (−33 kPa) and for the 0–5-cm depth at wilting point (−1500 kPa). This reflected significantly greater AWC under NT than CT at three depth increments (Table 6). The higher efficiency in retaining water in the soil under NT also implied greater water uptake by the crop, resulting in a greater barley yield in NT than CT in the driest growing season.

No-tillage decreased the total pore volume ($P < 0.10$) and modified the pore-size distribution compared to CT. The volume of large pores (>9 μm) was significantly reduced while smaller pore volume significantly increased under NT compared to CT (Table 7). In semiarid soils, FWC usually remains below field capacity for most of the growing season. For this reason, it is important to measure the volume of pores that store water between −33 and −1500 kPa (i.e. AWC). Most of the differences observed in the AWC between NT and CT were associated with water retained in soil pores having an equivalent diameter of 0.2–9 μm. More precisely, the difference in plant AWC was primarily due to a significantly greater frequency of small pores between 6 and 9 μm at all the three depth increments under NT than CT (Table 7). Similar results were also reported by Arshad et al. (1999) and Bescansa et al. (2006).

5. Conclusions

5.1. Scientific conclusions

The suppression of tillage resulted in increased penetration resistance of the tilled layer (0–15 cm) in the studied carbonate-rich degradation-prone soil, with natural low organic matter content, silty texture, and weak structure. However, other physical quality indicators, such as aggregate-size distribution, water stability and water retention characteristics were significantly improved after 7 years of continuous no-tillage (NT). Greater dry mean weight diameter and water stable aggregates percentage were observed under NT compared to in the area as a result of reduced mechanical disturbance and increased organic matter content. This was related to the development of a new pore-size distribution under NT compared to CT. Small pores (0.2–9 μm) occupied the majority of the pore volume at 0–5-, 5–15- and 15–30-cm depth intervals, whereas large pores (>9 μm) occupied the majority of the soil pore volume under CT. The relationship between pore-size distribution and the soil water retention characteristics resulted in an increase in the total plant-available water content for the three depth increments under NT compared to CT because of the greater small pores volume. Throughout the 2007–2008 growing season field water content and its availability for plants under NT were greater, especially for the driest months. This greater field water content also improved water uptake by the crop, resulting in a greater barley production under NT than CT in the driest year. The increased plant-available water content under NT, due to the improvement of soil structural properties (i.e. aggregate stability, pore-size distribution), helped thus to overcome the most limiting factor for crop production, and it seems to compensate for the greater penetration resistance in the studied soil.

5.2. Practical recommendations

Barley yield was twice as high with NT as with CT in the driest 2008 growing season, compared to similar yields in both fields in 2007. This trend to a temporal stabilization of barley production under NT was directly related to the observed greater plant-available water content in soil. We conclude that the implementation of NT resulted in a better functioning of the studied soil, in this semiarid area of the Ebro Valley. Farmers should consider adopting NT practices to compensate for the scarce and irregular precipitation pattern throughout the growing season.

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